

Research at the United States Naval Academy: More Than Meets the Eye

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Well known as the primary source of commissioned officers for both the Navy and Marine Corps, the United States Naval Academy (USNA) is an undergraduate educational institution with emphasis on technical education. This technical education is supplemented with design-and-build projects, hands-on demonstrations, and laboratory exercises using a wide variety of state-of-the-art test equipment. These laboratory facilities are leveraged by the civilian and military faculty to perform test and evaluation in support of cutting-edge research as well as answering operational questions from the Fleet. Of particular note are the modest costs associated with funded research at the Academy, the proximity of many other government agencies and laboratories in the Greater Washington, D.C., area, and the prior or current military experience of a significant fraction of the faculty. Described herein are several typical project efforts performed at the Naval Academy that were funded either by the Office of Naval Research, the Air Force Research Laboratory, or the Naval Research Laboratory. These examples are provided as a means to showcase the research and test capabilities that can be found at the Naval Academy.

Key words: Armor; coating; education; facilities; material properties, physics and engineering analysis; Naval Academy; collaborative; research; test and evaluation; training.

The Naval Academy was founded in 1845 in what is now historic Annapolis, Maryland. As the United States Navy has moved from a fleet of sail and steam-powered ships to a globe-spanning fleet of nuclear-powered submarines, surface ships, and supersonic aircraft, the Academy has changed also. The Naval Academy gives young men and women the up-to-date academic and professional training needed to be effective naval and marine officers in their assignments after graduation. Every day, as the undergraduate college of the naval service, the United States Naval Academy strives to accomplish its mission to develop midshipmen “morally, mentally, and physically.”

Every midshipman’s academic program includes a core curriculum that includes courses in engineering, science, mathematics, humanities, and social science, regardless of major. This is designed to provide a broad-based education that will qualify the midshipmen for practically any career field in the Navy or

Marine Corps. For those students who elect to major in engineering, the Division of Engineering and Weapons at the U.S. Naval Academy is composed of five departments, encompassing six academic majors. These majors are aerospace engineering, electrical and computer engineering, mechanical engineering, naval architecture, ocean engineering, and systems engineering. Midshipmen are immersed in a hands-on, project-based environment geared toward teaching real world engineering problem-solving skills by combining practical knowledge and a thorough understanding of mathematical and scientific fundamentals.

Naval Academy faculty, test facilities, and laboratory equipment

The Naval Academy’s engineering program is certified by the Accreditation Board for Engineering and Technology (ABET), with the most recent accreditation being granted in 2005. The faculty is nominally a 55% civilian/45% military mix, with the overwhelming majority of civilian professors holding

the Ph.D. degree and on a tenure track. The military instructors are further divided into two categories, with approximately 85% of the military members on a short duration tour of approximately 2 to 3 years, typically following an operational period with the Fleet or Marine Corps. The remaining 15% of military faculty are senior officers (O-5/O-6 pay grade) possessing Ph.D. degrees and assigned on a permanent basis. These officers have been selected for both their academic skills and their operational experience. Termed permanent military professors (PMP), this group of military professors tends to have extensive networks of contacts within the Navy's technical departments such as the Office of Naval Research, the various Warfare Centers, the Naval Research Laboratory, and the Naval Sea Systems Command. Additionally, many of the civilian professors tend to have developed strong ties to the Department of Defense (DoD) research community found in the Greater Washington, D.C., area. Between the civilian professors and the PMP cohort, significant amounts of research, test, and evaluation occurs at the Naval Academy, with strong support from the Academy administration. Funding is expected to be obtained by the participants, with only limited support available from Academy operational accounts. For fiscal year 2008, the total amount of externally supported research funding was approximately \$5.2 million distributed among 75 faculty members of the engineering and weapons division. The Naval Academy administration strongly encourages active faculty research, test, and evaluation for multiple reasons. An academic faculty that is performing cutting-edge research is viewed as improving the baseline knowledge necessary for successful classroom instruction. Research involving DoD-related topics is particularly encouraged as both the faculty member and indirectly the students taught by the research professor will be exposed to current technology issues facing the DoD establishment. Midshipmen are also encouraged to perform research projects as a method to allow students to gain a deeper understanding of specific facets of their chosen field of study. Since the Naval Academy is strictly an undergraduate facility, research projects tend to be tightly focused and constrained efforts that can be accomplished during the course of an academic year. Without graduate students to carry significant levels of research effort, the nature of research at the Academy also tends to be cyclic, with major portions of non-student-performed research occurring during the summer season, when the midshipmen are tasked with training evolutions out in the Fleet.

The Naval Academy engineering research, test and evaluation facility is state-of-the-art. On a departmen-

tal basis, specific instrumentation or equipment will be presented in the following section with the goal of providing an overview of the specific test and evaluation equipment and capabilities that currently exist at the Naval Academy.

The Aerospace Engineering department has one of the best equipped wind tunnel laboratories in the nation for an undergraduate-only institution. The department currently maintains and operates four subsonic wind tunnels. The largest of these has a test section of 38 inches \times 54 inches and can reach speeds of up to 200 mph. These wind tunnels are used by faculty and students in both research and classroom instruction. The department also has a supersonic wind tunnel capable of velocities with an upper range of Mach 3. With a test section area of 6 inches \times 6 inches, small models representing spacecraft re-entry vehicles or supersonic aircraft can be subjected to these high-speed airflows under a variety of conditions. Automated data collection systems allow for pressure, temperature, and force measurement from the various tunnels. Additionally, the largest facility in the Aerospace Department is the rotor lab. With this facility, full-size helicopter rotors or aircraft engine propellers can be tested at speed using various strobe camera, computer, and smoke visualization techniques. This facility provides invaluable research data for those interested in understanding the complex dynamics of helicopter flight.

The Electrical and Computer Engineering (ECE) department has developed strong capabilities in the area of biometric signal processing education and research. A continual effort is made by the Naval Academy to upgrade test and evaluation equipment to the most advanced biometric devices on the market. The ECE department's Electromagnetics and Wireless Lab (EWL) is an interdisciplinary research center focusing on all aspects of wireless communications, with applications that include data networks, sensor networks, robust and/or covert communications, networked communications, position location, software-defined radio, and antennas. The EWL combines theoretical and computational modeling with experimental testing.

The Mechanical Engineering department has developed strong capabilities in multiple research focus areas, predominantly in the areas of materials sciences, thermal/fluid mechanics, and mechanics of materials. Additionally, the department operates a subcritical nuclear reactor, an extensive fluid mechanics laboratory, and a material properties characterization facility. A combustion laboratory facility has been recently upgraded, permitting test and evaluation of a wide

range of internal combustion engines and is an extremely popular undergraduate research facility.

The Naval Architecture and Ocean Engineering (NAOE) department uses two towing tanks—one of 380 feet length, the other 120 feet length—for both educational and research purposes. Housed in the Naval Academy Hydromechanics Laboratory, faculty use the facilities for research of ship resistance and propulsion, ship motions in wind and waves, basic ocean wave mechanics, and wave-structure interaction. The Laboratory staff also performs testing under contract to various Navy, governmental, and private organizations.

The Weapons Systems Engineering Department Systems Engineering faculty supports the instruction of an interdisciplinary major whose primary objective is to provide an overall understanding of the analysis and design of complete engineering systems. Emphasis is on mathematical modeling, analysis, synthesis, control, and simulation. Typical systems are electromechanical devices containing embedded computer controllers. Current work is being conducted in autonomous unmanned vehicle control, improvised explosive device (IED) defeat systems, and improved control systems for robotic devices.

Specific examples of research, test, and evaluation at the U.S. Naval Academy

In the Composites Manufacturing lab, material processing capabilities range from autoclave processing (4-foot diameter, 6 feet long, aerospace grade, capable of 850°F and 250 psi with personal computer [PC] monitoring and control) to a wide variety of out-of-autoclave processes, including resin infusion, resin transfer molding, compression molding, filament winding, and wet layup. The composite materials facility also has state-of-the-art equipment for evaluation of composite materials repairs. *Figure 1* provides a view of the composites manufacturing laboratory equipment.

In the Composites Test and Characterization lab, extensive physical characterization of advanced composites for material modeling can be performed, coupled with composites processing quality assurance evaluation. The Academy has extensive facilities for optical and electron microscopy of composites meso-structures, which, when coupled with the extensive mechanical testing capabilities, present the ability to perform studies of process/property relationships for a wide array of advanced materials and applications.

Recent work has focused on processing optimization for the lamination of transparent ceramic armor (supported by U.S. Army Research Laboratory), damage tolerance evaluation of honeycomb sandwich structures (supported by the Office of Naval Research), and material characterization and modeling of pitch



Figure 1. Four-foot diameter autoclave in the Composites Manufacturing lab.

fiber reinforced laminate composites (supported by Northrop Grumman Oceanic Systems.) The Academy also has extensive nondestructive test and inspection capabilities located in the Nondestructive Evaluation lab.

The Naval Academy Mechanical Test lab has a full spectrum of testing capabilities: a 200 kip universal tester, a tension/torsion machine, a spring-assisted drop weight impact tester, hydraulic load testers for cyclic fatigue testing, and several electromechanical load frames for general purpose materials testing.

Recent work has included a Navy project to evaluate the strength and impact resistance of hybrid steel to composite joints. The Naval Academy performed static tension tests as well as dynamic impact tests of two candidate hybrid joint configurations (manufactured as part of an Office of Naval Research Small Business Technology Transfer [ONR STTR] program). This testing was performed in collaboration with an investigator in the United Kingdom who was funded in part through the Defense Science and Technology Laboratory (DSTL) as well as ONR-Europe. The testing involved both midshipmen and an ensign.

Another recent example of collaborative research at the Academy consists of a recent Air Force Office of Sponsored Research Multi-University Research Initiative (AFOSR MURI) initiative to develop an integrated multi-functional coating system for military applications; various cold spray and thermal spray methods were pursued to deposit metallic coatings and evaluate their performance (Cadney et al., in press). It was required that the resulting coatings be easily field applied and have a range of functions to improve corrosion performance and coating adhesion, and to provide active corrosion protection through the use of nano-crystalline or amorphous matrix metallic glasses such as the Al-transition metal (TM)-rare earth (RE) glasses.

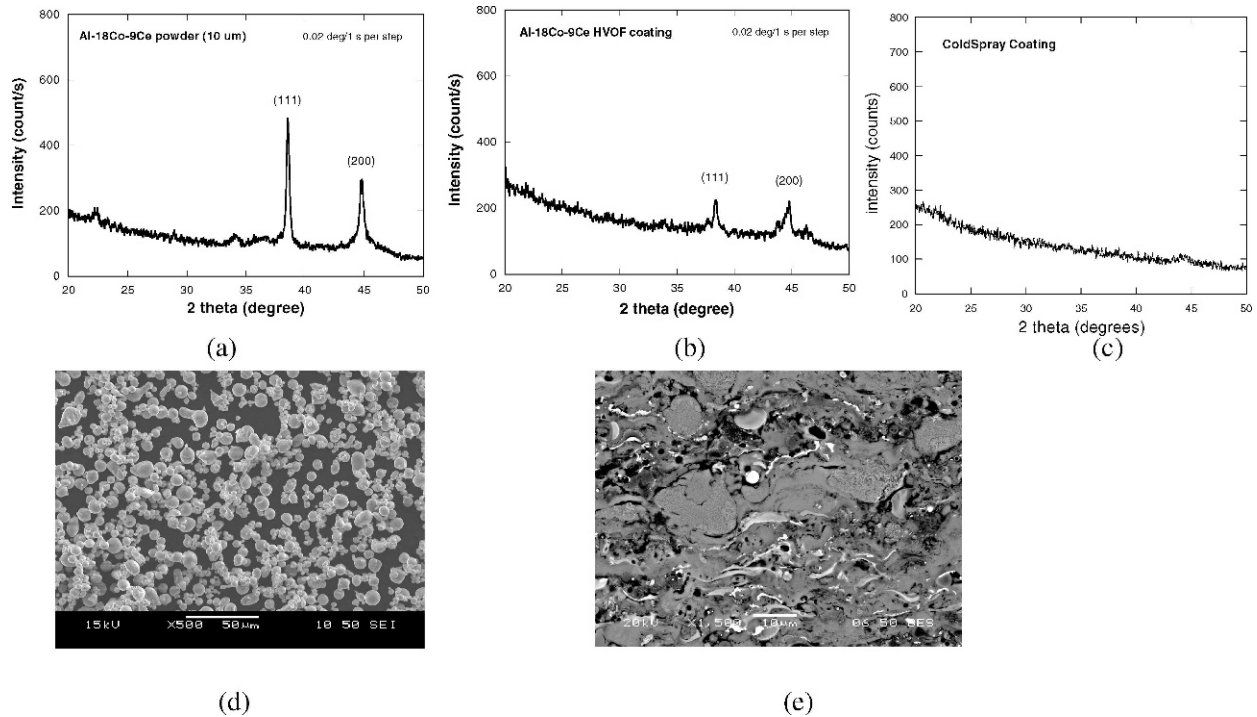


Figure 2. X-ray diffraction patterns of Al-18Co-9Ce feedstock powders, high velocity oxygen fueled (HVOF) coating, and pulsed thermal spray (PTS) coating (a, b, c) and Scanning Electron Microscopy (SEM) images for the powders versus the resulting HVOF coating (d, e).

Aluminum and aluminum alloy coatings were deposited in air from powder stock using several thermal spray techniques to evaluate the corrosion/fatigue performance as a function of thermal spray. Some preliminary cold spray coatings were evaluated for comparison and the results deemed promising. Initial experimentation on the application of amorphous cladding onto AA2024-T3 employed pure aluminum and demonstrated that a coated material with improved corrosion and fatigue properties was achievable. Comparison of the microstructures, mechanical properties, fatigue, and pre-corroded fatigue properties of samples with numerous types of thermal spray coatings, as well as samples of bare AA2024-T3 and Alclad™ AA2024-T3, revealed that HVOF is the most promising thermal spray process for the deposition of aluminum coatings from traditional feedstock powders. In particular, high velocity oxygen fueled (HVOF) coatings greatly increase the fatigue and pre-corroded fatigue lifetimes of the AA2024-T3 substrate. Additionally, coatings of Al-Co-Ce alloys were deposited from powders by thermal spray and cold spray processes.

X-ray diffraction for the HVOF process indicated that feedstock powders were nano-crystalline, and the deposited coatings demonstrated reduced crystallinity as shown in *Figure 2*. A modified form of HVOF, pulsed thermal spray (PTS) has been used to deposit

amorphous or nano-crystalline coatings using traditional crystalline feedstock. PTS coatings tend to demonstrate a higher degree of amorphousity, while coating hardness values were higher and fatigue lifetimes were lower than expected. The variance in values from that expected for amorphousity, hardness, and fatigue lifetimes were most likely due to high content of cobalt (Co) and cerium (Ce) and processing effects. Because the mechanical properties, especially fatigue properties, are essential for the use of these coatings in aircraft applications, processing conditions as well as substrate preparation must be optimized, or the composition altered, to satisfy the requirements for mechanical and corrosion properties. As a result of transition funding from ONR, a parametric study is now underway to define the processing parameters for HVOF and PTS to lower hardness and enhance fatigue life. Additional chemistries have been produced in ingot form and atomized into powders having a range of sizes.

The Academy has recently upgraded its capability to perform strain-rate dependency testing of engineering materials with the provision of a Split-Hopkinson Pressure Bar (SHPB) by the Naval Surface Warfare Center, Dahlgren Division. A SHPB is used to measure the change in mechanical properties such as yield strength, work hardening, and ductility, all of which can vary with strain rate. A SHPB is capable of



Figure 3. Midshipman conducting tensile testing of copper specimens in support of Electromagnetic Launcher (EML) program.

achieving the highest uniform uniaxial stress loading of a specimen at strain rates on the order of $10^3/s$. Stress waves are generated in an impact bar using a gas-driven striker mechanism. The dynamic stress-strain response of the material is captured via instrumentation and then evaluated using embedded software. The SHPB was provided by the Naval Surface Warfare Center, Dahlgren Division, and has been extensively upgraded with new data collection systems and specimen mounting mechanisms.

Preliminary testing of copper has been conducted in support of the Navy's Electromagnetic Launcher (EML) program (Rice et al., 2008), and efforts are underway to test prototype ceramic armor specimens in cooperation with the Naval Surface Warfare Center, Indian Head Division. Figure 3 shows a midshipman conducting preliminary material testing in support of the SHPB test of copper, and Figure 4 provides a close



Figure 4. Split Hopkinson Pressure Bar (SHPB), with gas gun and gas source in right foreground and impact bar on left-hand side of the image.



Figure 5. Midshipmen conducting research using Split Hopkinson Pressure Bar (SHPB).

view of the gas gun used to drive the striker mechanism used in the bar. As with nearly all research efforts at the Academy, midshipmen are intimately involved with the process, as shown in Figure 5.

Another effort to analyze material properties is a collaborative effort to perform spectrum load crack growth testing of 7050-T7451 plate. Testing was performed for Transverse-Longitudinal (T-L) and Longitudinal-Short Transverse (L-S) specimen orientations to determine the influence of spectrum truncation on fatigue crack growth rates and overall life. This effort was funded through the Joint Strike Fighter Program Office, Naval Air Systems, and the Air Force Research Laboratory.

This highly oriented aluminum plate material is used in several existing military fighter aircraft as well as both military and commercial transport aircraft with continuing evaluation as a candidate material for future designs. This testing was performed on center-hole (double crack), flat, rectangular tensile specimens machined from material blanks cut from 4-inch plate, using the test device shown in Figure 6. Additional comparison T-L tests were also accomplished using blanks from available 7050-T7451 0.5-inch plate. Spectrum loading used for the testing was based on a nominal fighter wing bending moment spectra, and levels of testing were composed of baseline (5 percent), plus 20 percent and 30 percent range truncation levels. The target, ordered stress levels were based on legacy and predicted use of U.S. fighter aircraft. Stress levels were calculated using results of numerical analysis combined with past use and should not be assumed to be, nor the direct result of, flight test data.

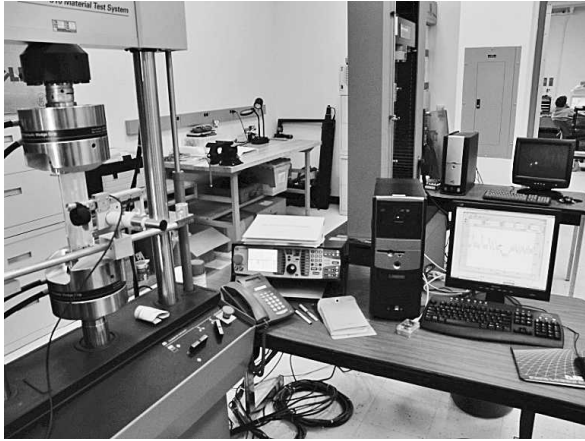


Figure 6. Fatigue testing equipment consisting of 22,000-lb load frame, hydraulic wedge grips, and a traveling telemicroscope for in-situ crack detection.

Results produced representative trends in life increases for truncation levels relative to 5 percent truncated levels for the L-S and T-L orientation specimens. Crack growth rate data was recorded and comparisons were shown for varied orientation and crack length. Findings show that although relatively small changes in life are experienced due to orientation, L-S-oriented plate material life is affected by the greatest extension. Crack growth rates for shorter cracks in the L-S material greatly exceed growth rates in the T-L-oriented material. Characteristics of splitting, crack wandering, branching, and shielding were observed in the L-S specimen tests and are shown in Figure 7. These potentially undesirable characteristics resulted in temporary crack arrest or retardation in the direction perpendicular to loading and resulted in

overall specimen rupture well beyond predicted critical crack lengths (Schubbe, 2009).

A final example of cooperative test and evaluation between the Academy and a government lab is described as follows. An attempt to develop modeling and simulation methodologies for the assessment of structural survivability in aerospace structures was conducted under the sponsorship of the Naval Surface Warfare Center, Dahlgren Division. Such an undertaking is considerable because of the inherent complexity of the structures and loads involved. Additionally, confident deployment of any methods will require an extensive and rigorous program of model verification and physical testing.

With these larger goals in mind, a coordinated effort was made to model, test, and verify the structural response of real aerospace rib-skin structures in both undamaged and damaged configurations. The structures considered were approximately 9 feet long, aluminum-skinned cylinders 30 inches in diameter. The structural skin was riveted to z-shaped aluminum ribs and longerons. Additional internal structural components, including bulkheads and complex stiffeners, were present. All structures were instrumented with strain gauges and string potentiometers along the ventral axis of the cylinder and tested until failure in cantilever bending, as shown in Figure 8. Testing of the structures required the development of a special cantilever bend rig. In addition, high-fidelity finite element models of the test structures were constructed and solved for pure cantilever bending. The finite element models were used in both the design of the experiment and construction of the test rig as well as to

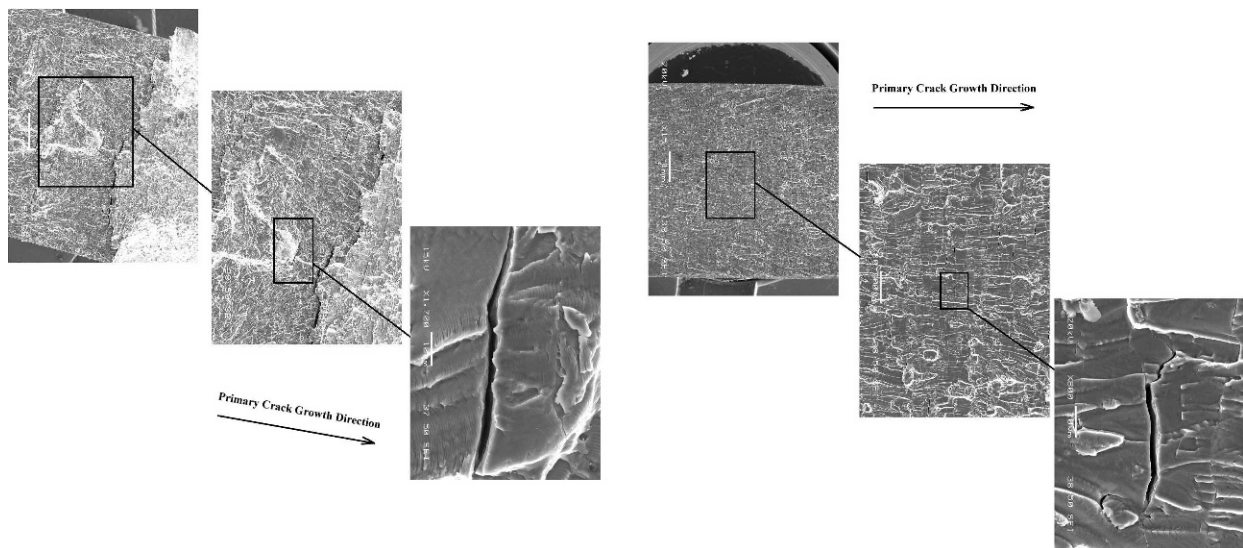


Figure 7. Crack progression and splitting in Longitudinal-Short (L-S)-oriented specimens.

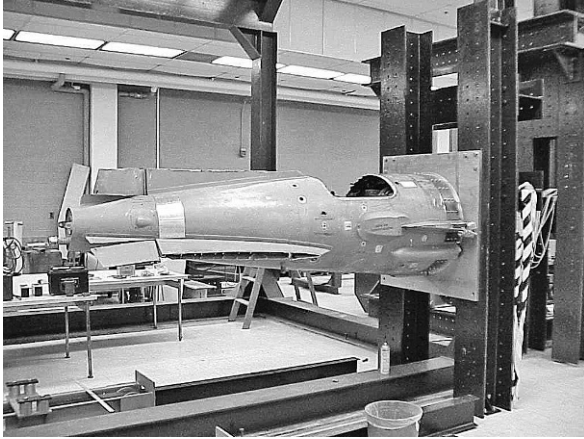


Figure 8. Rear portion of missile fuselage mounted in cantilever bend test device.

predict the structural response of both the damaged and undamaged structures (Burkhardt and Joyce, 2007).

Conclusion

As discussed previously, the amount of research, test, and evaluation that is conducted at the U.S. Naval Academy is surprisingly varied in scope, supported by cutting-edge test equipment housed in well-equipped and staffed facilities; and, given the limitations of time and staffing placed on faculty members, surprisingly sophisticated. The research efforts that are ongoing at the Academy are truly more than initially meets the eye. □

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References

- Burkhardt, J. and P. Joyce. 2007. A cantilever bending rig for testing symmetric and asymmetric structures exhibiting large deflections. *Experimental Techniques*. 31 (3): 43–47.
- Cadney, S., G. Goodall, G. Kim, M. Brochu, and A. Moran. In press. The transformation of an Al-based crystalline electrode material to an amorphous deposit via the ElectroSpark welding process. *Journal of Alloys and Compounds*.
- Rice, C. J., C. M. Sapienza, L. Brown, and P. Joyce. 2008. The influence of strain rate on the mechanical response of copper. In *Proceedings of the National Conference on Undergraduate Research (NCUR) 2008*, April 10–13, Salisbury, Maryland: University of North Carolina-Asheville.
- Schubbe, J. 2009. Evaluation of fatigue life and crack growth rates in 7050-T7451 aluminum plate for T-L and L-S oriented failure under truncated spectra loading. *Engineering Failure Analysis*. 16 (2009): 340–349.