

Institute for Manufacturing and Sustainment Technologies

A U.S. Navy Manufacturing
Technology Center of Excellence

iMAST

Q U A R T E R L Y

2000 No.3

First Annual Naval-Industry R&D Partnership Conference Concludes

iMAST recently participated in the first annual Office of Naval Research conference designed to promote dialogue between government, industry, academia, and the U.S. Navy. Established to leverage corporate research and development efforts for the Department of the Navy, a series of interactive breakout sessions provided forums to seriously discuss the challenges facing the defense industrial base. Held in Washington D.C., a progressive agenda was established which included:

Attracting Commercial Partners

This track included sessions addressing initiatives to connect the Navy's R&D community with national, regional, and state economic development agencies. It also provided an opportunity to articulate defense needs and an understanding of industrial capability. Venture companies also provided presentations on technology development and commercial enterprise with case studies noted. Further topics included: partnering, globalization and national security, eBusiness information exchange, and technology transfer in the computer software sector.

Creating Incentives/Bulldozing Disincentives

This track discussed intellectual property rights and the challenge barriers industry has with government. Value-driven procurement, export controls, incentivizing government and industry, and partnering (military and civilian sectors) were also elements of the agenda.

Enhancing the Technology Insertion Process

Lean sustainment to radically reduce operating and maintenance costs through the insertion of commercial technology and practices highlighted this track. DoD 5000 implementation in the Department of the Navy, strategies for technology insertion, disruptive technologies, advancing the pool of available technologies, and new methods/practices/tools for the management of technology were also highlighted.

Meeting Navy Program Managers and Prime Suppliers

This track provided a unique opportunity to meet with various members of the Naval Systems Commands (NAVAIR, NAVSEA, and MARCORSYSCOM).

The first annual Naval-Industry R&D Conference was considered highly successful. We highly recommend interested parties consider attending next year's conference. As such, we will keep you informed in our calendar of events section.



The Honorable Jerry M. Hultin, Undersecretary of the Navy, pauses for a photo during his visit at the iMAST exhibit booth. Shown with Mr. Hultin are Dr. Tom Donnellan (left), associate director materials and manufacturing, ARL Penn State, and Mr. Bob Cook (right), director of ARL Penn State's iMAST program.

**FOCUS ON
MATERIALS
PROCESSING
(COATINGS)**

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DIRECTOR'S CORNER

Charting a Course

I was honored to be selected as the Director of the Institute for Manufacturing and Sustainment Technology (iMAST). I intend to apply my extensive experience as a fleet



operator and acquisition program manager to lead iMAST in accomplishing the objectives of the Navy's ManTech Program. I know firsthand the benefits of technology in enhancing the performance of fleet systems and improving the quality of life of our Sailors and Marines. In this time of constrained budgets, I am responsible to ensure maximum efficiency of spending, while recognizing that failure is also part of research and development.

The overall objective of the Department of the Navy (DoN) ManTech Program is to significantly improve the affordability of DoN systems by engaging in manufacturing initiatives that address the entire weapon system life-cycle. More specifically, program objectives are to:

- Reduce the risk and cycle time associated with the transition from R&D to full scale production by developing and implementing advanced manufacturing processes and equipment
- Extend the life of current DoN systems by providing manufacturing technologies to support the maintenance, repair, and overhaul of these systems, and
- Strengthen the industrial base by providing maximum dissemination of the results of all ManTech projects and the best manufacturing practices of government and commercial facilities.

The Office of Naval Research is focusing on Future Naval Capabilities (FNC) to decide where to concentrate funding. One of the FNCs is Total Ownership Costs. I see an opportunity to use advanced research funding to mature a technology to the point where Manufacturing Technology can take the process and mature it to the point of implementation in an acquisition system. Here is a great opportunity for synergy.

Navy and Marine Corps Program Managers can use ManTech as a tool to assist in solving manufacturing problems. ManTech can take an immature, yet innovative process with higher risk, and improve it to the point where a program manager will accept the risk of implementation. There are several aspects that I believe will improve the process. First, we must have active participation from the program office. A clear definition of the problem and goal is critical. Here, cost sharing with the program office can leverage available ManTech funding while encouraging involvement in the process. Second, we must identify the industry or depot partner to ensure a smooth transition to implementation. Third, projects must be responsive and efficient, and should rapidly complete. New projects should start each year to ensure iMAST is responsive to the Navy's needs.

iMAST will only be successful through teaming with ONR, the Systems Commands, the program offices and the fleet. We must bring innovative and relevant research to bear to solve today's and tomorrow's problems. I am confident that we can provide a strong contribution towards making our warfighters the best in the world.

Bob Cook



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Electron Beam-Physical Vapor Deposition Technology: Present and Future Applications

by Jogender Singh, Ph.D. and Douglas E. Wolfe

The role of coatings is significant in the advancement of technologies for applications in the optics, auto, and aerospace industries. A high percentage (75%) of aircraft engine components is coated by metallic or ceramic coatings for the purpose of enhancing performance and reliability. Thus, there is a continuous effort to engineer surface properties to enhance the life of components under severe environmental conditions where corrosion, high-temperature oxidation, and wear are concerns. Similarly, multi-layered ceramic and metallic films are used in the fabrication of microelectronic components. Processes to control thin film properties are also extremely important in the microelectronic industry.

Industrial coating techniques (exclusive of painting and electroplating) can be broadly classified into three groups: physical vapor deposition (PVD), chemical vapor deposition (CVD), and spray processes. Each process can again be sub-classified based on the source of energy used for the deposition of coatings as shown in Table 1. Each of these processes has advantages and disadvantages.

The electron beam-physical vapor deposition (EB-PVD) process has overcome some of the difficulties associated with the CVD, PVD (sputtering), and metal spray processes. EB-PVD is a simple process in which a focused high-energy electron beam is directed to melt evaporant material(s) in a vacuum chamber (Figure 1). The evaporated material condenses on the substrate's surface or components resulting in coating formation. Depending upon applications and substrate materials,

external heating is applied to substrate for enhancing the metallurgical bonding between the coating and the substrate. This is a line-of-sight process. However, uniform coatings are applied on

Table 1. Coating Deposition Techniques.

Spray Deposition processes	
Thermal spray	
High-Velocity Oxy-Fuel (HVOF)	
Detonation gun (D-gun)	
Chemical Vapor Deposition processes (CVD)	
Low-pressure CVD	
Plasma-enhanced CVD	
Photochemical and laser CVD	
Physical Vapor Deposition processes (PVD)	
Thermal evaporation	
Electron beam evaporation	
Sputtering	
– Balanced and unbalanced magnetron sputtering	
– Direct current diode sputtering	
– Radio frequency sputtering	
– Triode-assisted PVD	
Ion Implantation and Ion Plating	

components such as turbine airfoils by maneuvering within the vapor clouds. Application of the EB-PVD process is unlimited—from solar reflectors, microelectronics, auto parts and aerospace components to precision net-shaped formation of components which

depend on evaporating unit capabilities.

There are three components (EB-gun, water cooled copper crucible and vacuum chamber) in the EB-PVD unit that enhances its flexibility and applications. EB gun could be self-accelerated straight (Figure 1) or



Figure 1. Schematic diagram showing straight electron beam gun.

electromagnetic deflected through 180 or 270°. Similarly, evaporant material is placed in a water-cooled copper crucible, which could be either pocket type for small quantity evaporation application or continuous ingot feeding through the crucible for larger quantity evaporation. Flexibility in the application of the EB-PVD unit is enhanced by using many EB guns and continuous multiple ingot feeding system (Figure 2, see next page).

The EB-PVD Process

ARL Penn State's industrial pilot Sciaky EB-PVD unit has six electron beam guns, four of which are used to evaporate the coating materials and two of which are used to preheat the substrate to facilitate coating adhesion. Each gun has a 45-kW capacity. The chamber will accommodate up to three ingots ranging in size from 7–15 cm in diameter and 70 cm long. The overall dimensions of the production



PROFILE

A respected leader in his field, with research experience in academia, industry and national labs, Jogender Singh is a senior scientist with ARL Penn State. Dr. Singh's expertise includes coatings and surface modification of materials by various techniques including laser and the EB-PVD process. He is actively working in the synthesis of nano-particles and characterization by various techniques including SEM, X-ray, and TEM.

Prior to joining Penn State, Dr. Singh worked for NASA and GE in development of new materials and coatings for aerospace applications. His interests continue to be surface engineering and technology enhancement for various applications. Dr. Singh is a Fellow of ASM, FIM, and FAAAS. He can be reached at (814) 863-9898, or by e-mail at: <jxs46@psu.edu>.

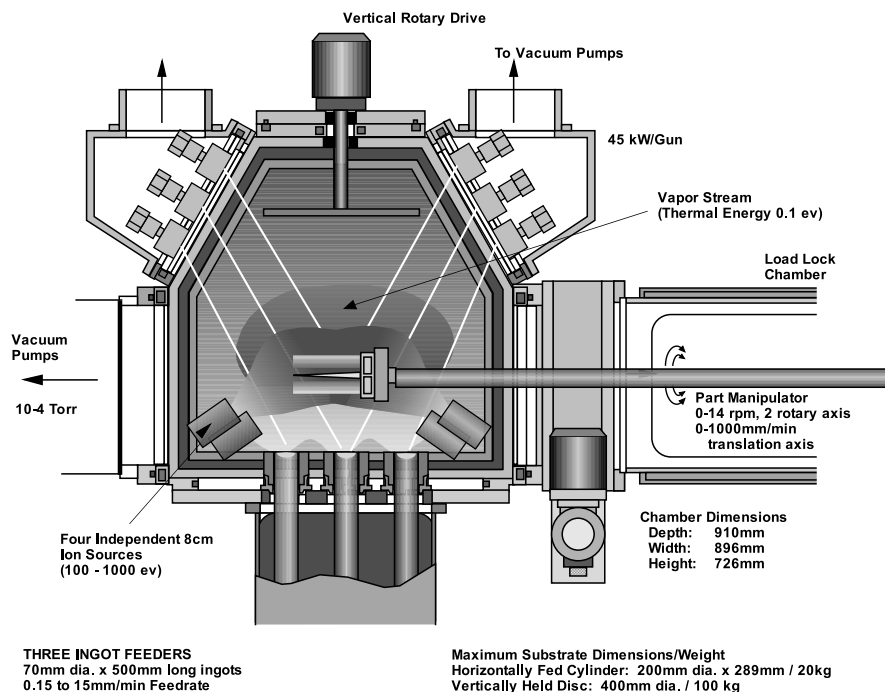


Figure 2. EB-PVD schematic.

unit is about 1 cubic meter. The maximum diameter of the substrate (with vertical rotation) that can be accommodated is about 400 mm; and can be rotated at a speed of 5.5 to 110 rpm with a maximum load of about 100 Kg. The unit also has a horizontal sample holder with a three-axis part manipulator: two rotary axes of 0–14 rpm and a 0–1,000 mm/min translation axis. It can carry samples weighing up to 20 kg.

Advantages of the EB-PVD Process

The EB-PVD process offers extensive possibilities for controlling variations in the structure and composition of condensed materials. For example, the coating compositions can be varied continuously, as in so-called Functional Graded Coatings (FGC). Also, coatings comprised of alternating layers of different compositions can be made. These multilayered coatings can be applied on top of the FGC. The EB-PVD process offers many desirable characteristics such as relatively high deposition rates (up to 150 $\mu\text{m}/\text{minute}$ with an evaporation rate of $\sim 10\text{--}15\text{ Kg}/\text{hour}$), dense coatings, composition

control, columnar and polycrystalline microstructure, low contamination, and high thermal efficiency. Coatings produced by the EB-PVD process usually have a good surface finish and a uniform microstructure. The microstructure and composition of the coating can be easily altered by manipulating the process parameters and ingot compositions. Thus, multilayered ceramic/metallic coatings can be readily formed and various metallic and ceramic coatings (oxides, carbides, and nitrides) can be deposited at relatively low temperatures. Even elements with low vapor pressure such as molybdenum, tungsten, and carbon are readily evaporated by this process.

The attachment of an ion beam-assisted source to the EB-PVD system offers additional benefits such as forming dense coatings with improved microstructure, interfaces, and adhesion. In addition, textured coatings, that are desirable in many applications, can be obtained. The state of the internal stresses can be changed (i.e., from tensile to compressive) by the forcible injection of high-energy ion beams (100–1,000 eV). A high-energy ion beam (as a source of energy) is quite often used to clean the

surface of the specimen inside the vacuum chamber prior to coating. The cleaning enhances the mechanical bonding strength between the coating and the substrate.

Many coating materials are used both in the microelectronics and heavy manufacturing industries. For example, oxides of aluminum, yttrium, zirconium (i.e., Al_2O_3 , Y_2O_3 , ZrO_2 , respectively) are used in microelectronic industries as an insulator, buffer layer, or diffusion barrier coating. The thickness of coatings for such applications is $< 10\text{ }\mu\text{m}$. On the other hand, in the aerospace and auto industries, oxide coatings are used for enhancing the performance of components under severe environmental conditions such as corrosion, oxidation, and wear. The coating thickness for such applications is typically $> 10\text{ }\mu\text{m}$. Such coatings are often called thermal barrier coatings (TBC).

Multilayered metallic or ceramic coatings are often applied on the components to achieve desired properties. Properties and performance of the coating also depends upon the coating thickness. It has been well established that multilayered coatings with thickness $< 1\text{ }\mu\text{m}$ offer superior structural and physical properties due to refined microstructure in the coating and good interfacial bonding with the substrate.

In summary, the choice of deposition technique is determined by the application for the coating, the desired coating properties, cost or production rate available from the process, temperature limitation of the substrate, uniformity or consistency of the process, and its compatibility with subsequent processing steps. Chemical and physical conditions during the deposition reaction can strongly affect the resultant microstructure of the coating (i.e., single-crystalline, polycrystalline, amorphous, epitaxial).

Applications of the EB-PVD Process

The versatility of the EB-PVD process is very wide and new varieties of coatings

and materials continue to be developed. Some successful applications of the EB-PVD and ion beam-assisted EB-PVD processes are given below.

Alternative to Hard Chromium Electroplating—Corrosion-Resistant Coatings

Chromium (Cr) electroplating is well known to be an environmentally hazardous process. The Cr plating process is normally used in areas where wear, corrosion, and oxidation (<600° C) are factors in equipment performance. An environmentally friendly process which provides the same or improved wear, corrosion, and oxidation protection is required. To achieve this goal, two challenges must be met: (1) identify/develop potential candidate materials for the replacement of Cr and (2) develop/identify a process for applying the candidate coating materials.

A unique characteristic of EB-PVD is that it meets the above mentioned challenges and also can be used to tailor coatings for specific applications. With the EB-PVD process, corrosion-resistant materials can be applied economically on the surface where they are most needed. Applications for these coatings range from brass lighting fixtures to landing gear and other components of aircraft and helicopters.

Figure 3a is a photograph of a helicopter landing gear showing localized surface damage that needs to be repaired. The current repair process is the chemical stripping of the chromium coating followed by replating, baking, and machining of the entire component. Localized refurbishment of the landing gear (Figure 3b) was successfully demonstrated by applying Cr in the EB-PVD chamber. Unlike thermal spray coating, these deposits had a dense microstructure with good metallurgical bonding with the base metal. In addition, microcrack sealers are not required. The cost saving is expected to be more than 20–30% with improved component life and performance. Efforts are underway to identify alternative chromium replacement materials (deposited below

500° F) which will have superior physical and mechanical properties under severe environmental conditions.

Coatings for the Turbine Industry

The EB-PVD process has been used successfully in applying oxidation and wear-resistant metallic and ceramic coatings at high deposition rates on large components such as turbine blades. The thickness of these coatings varies from 0.1 to 5 mm depending on the application. Thick metallic-ceramic coatings (including TBC) were previously applied by the spray processes. The life of the plasma-sprayed TBC-coated turbine component was limited due to the inhomogeneous microstructure, unmelted particles, voids, and poor bonding with the substrate. When the same coating is applied by the EB-PVD process as is being done commercially, the life of the component is reported to increase by a factor of two due to the porosity controlled columnar microstructure, smooth surface finish, and improved metallurgical bonding with the substrate (Figure 4). Future thrusts are in producing a compositional gradient and oxidation-resistant bond coat as an intermediate layer followed by low-conductivity, porosity-controlled TBCs. Additional future efforts include developing advanced spar-shell structures for turbine blades. Overall, it is anticipated that the DoD goal of doubling thrust-to-weight ratios for aircraft engines can be achieved.

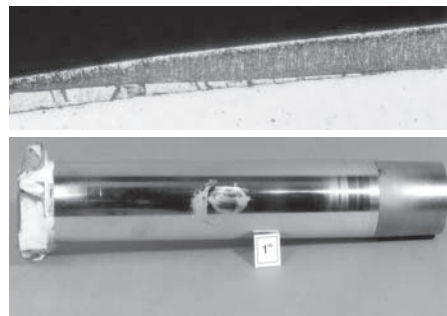


Figure 3. (a, top) The localized damage in the helicopter (H-53) landing gear, which was refurbished with Cr by EB-PVD (b, bottom). The Cr coating had a good metallurgical bonding with the substrate ($T_s \approx 1,000^\circ \text{F}$).

Coatings for the Tool and Die Industries

A remarkable improvement in tool life was observed (at least 400%–600%) after applying hard wear-resistant coatings (such as TiC, TiN, TiAlN, and TiZrN). Performance of these wear-resistant coatings depends both on composition and the coating process. Nitride coatings are commercially applied by the PVD process (Table 1) whereas carbide coatings (such as TiC, HfC, ZrC) are applied by CVD. Since CVD is a high-temperature process (800–1200° C), many temperature-sensitive substrates cannot be coated by this method.

EB-PVD has overcome some of the problems associated with CVD, including environmental issues, waste of hazardous chemical gases,

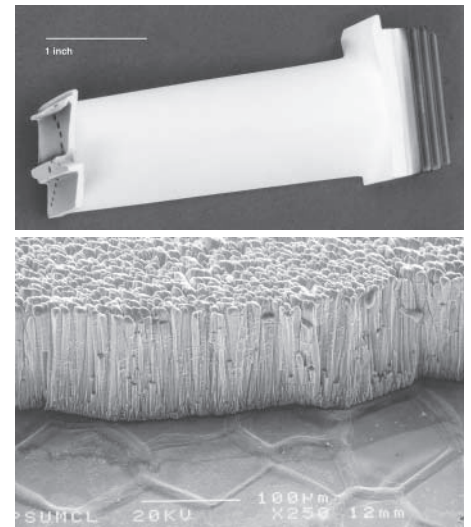


Figure 4. Turbine blade coated with TBC by EB-PVD (a, top) having columnar microstructure (b, bottom).

undesirable high-temperature reactions, and low deposition rate. Hard coatings such as TiC, HfC, ZrC, TiN, and TiB₂ have been economically produced by ion beam-assisted EB-PVD at relatively low temperatures. Multilayered coatings composed of TiC/Cr₃C₂ have been successfully produced by the co-evaporation of the Ti, Cr, and graphite ingots in the EB-PVD chamber (Figure 5, see next page). The future thrust is in developing superhard multilayered coatings composed of Al₂O₃/TiC and TiB₂/TiC/Cr₃C₂ by the ion beam-assisted EB-PVD.

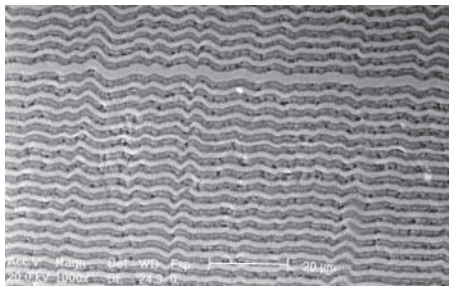


Figure 5. Multilayered TiC/Cr₃C₂ coating produced by co-evaporation of Ti, Cr and graphite ingots in the EB-PVD chamber. The deposition rate is about 50 $\mu\text{m}/\text{minute}$. The thickness of each layer is about 1.25 μm and the total coating thickness is 1 mm.

Optical Coatings

The ion beam-assisted EB-PVD process has been successfully used to apply thin films of various materials including Ag, Cu, ZrO₂, TiO₂, Al₂O₃, and SiO₂, for optics, high-performance solar cells, and sensors. Performance of these films depends on the quality of the thin films including uniformity, density, and texture.

Microelectronic Coatings

High-quality, defect-free epitaxial or textured thin films are desired in the microelectronic industry. Varieties of ceramic and metallic multilayered coatings are used as a buffer layer to achieve properties such as diffusion barrier coatings for epitaxial growth textured thin films. To grow epitaxially superconducting thin films of yttrium barium copper oxide (YBCO) on stainless steel plates, various multilayered oxide films (Al₂O₃ or Y₂O₃, ZrO₂, and CeO₂) are deposited by various techniques including sputtering, ion beam-assisted sputtering, and laser ablation. Such intermediate layers are essential to obtain good quality, superconducting thin films. The thickness of these coatings varies from 100 Å to 1 μm . These same coatings can also be obtained by the ion beam-assisted EB-PVD process at a relatively low cost.

Precision net shaped forming components

Refractory metals are very attractive materials for high temperature structural and energy system applications such as solar powered rocket engines, heat

exchangers, and space and missile propulsion systems. However, it is very difficult to manufacture precision net shaped form components made of refractory metals such as hafnium and rhenium. Refractory metal components are fabricated by either powder metallurgy (P/M) or CVD. Due to difficulties encountered in the P/M fabrication and shaping of refractory parts, CVD is often used in fabricating thin walled, small diameter or complex shaped components and for coatings on carbon, ceramic or metal components. However, CVD process also has shortcomings. For instance, rhenium deposition is obtained by decomposing rhenium penta-chloride precursor gas at 1200^o C. CVD rhenium deposit often contains entrapped gas as an impurity resulting in lower physical and mechanical properties. In addition, carbon diffuses exponentially into rhenium due to high temperature deposition resulting in significant stresses into coating and contributes to premature failure. A typical, good quality rhenium coating deposition rate is 3-5 mm/hour. CVD is not considered to be a line-of-sight process, however, CVD rhenium coatings on thrusters and graphite balls do not provide uniform coatings due to limited flexibility in maneuvering parts in the reaction chamber and gas flow dynamics. Currently, only one component is manufactured at a time in a reactor chamber. In addition, CVD coating produces a columnar microstructure, which is undesirable for structural applications and is destroyed by periodically taking out the coated components followed by surface mechanical grinding and recoating. Shortcomings of CVD process were addressed by EB-PVD where refractory ingot was evaporated and deposited on a mandrel at relatively low temperatures (700 to 1000^o C) with minimum impurities. Microstructure of EB-PVD coatings is comparable with CVD and is generally having columnar morphology. It is important to mention here that the

grain size of EB-PVD coatings is possible to refine by interrupting columnar grain growth during deposition process. This has been demonstrated in rhenium material. Hardness of the rhenium deposit was increased to 283 VHN by refining microstructure with grain size less than 10-50 mm.

EB-PVD Research Facilities and Capabilities at Penn State

1. EB-PVD industrial coater
Six 45-kW guns, three continuous feed ingots, chamber size: 1 cubic meter with load lock chamber and Kauffman type ion source.
2. Ion Beam-Assisted EB-PVD general coater
One 10-kW gun, four hearths, cold cathode ionization source, cryo-pump, chamber size: 66 cm $\times$ 60 cm.
3. EB-PVD
Two 15-Kw guns, two hearths, cryo-pump, chamber size: 66 cm $\times$ 60 cm.

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Pennsylvania Governor Tom Ridge congratulates Dr. Singh at the society's annual awards dinner held recently in Cincinnati, Ohio.

Singh Recognized by ASM

Dr. Jogender Singh, a senior scientist with ARL, was recently designated a Distinguished Fellow Member of the American Society of Metals (ASM) International and cited for "exceptional contributions in the applications of laser beam processing to the synthesis of nanoparticles, coatings, surface modification, thin films, welding, and cutting."

DoD Laser Conference Convenes

A national conference on laser applications in the DoD was presented by ARL's Laser Processing Division during September at Penn State. The conference, co-sponsored by the joint DoD ManTech directorate, featured presentations by key service reps, maintenance and manufacturing professionals, industry experts, and members of the research community at large. Issues addressed included development and implementation of emerging laser technologies for application in reducing cost and improving the performance of military weapon systems. Over 120 individuals from government, industry, and academia concentrated their discussions on laser technologies used in the manufacture, fabrication, and repair of DoD systems. A topical session concerning laser weapon applications was also included. Vision statements for the various sessions were provided by Mr. Steven Linder, Office of Naval Research; Ms. Carol Gardinier, Army Materiel Command; and Dr. Steven LeClair, Air Force Research Laboratory. For more information on iMAST's laser application programs, contact Dr. Rich Martukanitz at (814) 863-7282 or e-mail <rxm44@psu.edu>.



Topical Workshop Hosted by Laser Processing Division

ARL's Laser Processing Division (LPD) recently hosted a topical workshop entitled: "Practical Utility of Simulation Technology in Laser Materials Processing". Topical workshops are held periodically by the LPD and are used to review very specific technologies related to laser processing at an in-depth level necessary for transitions into manufacturing systems arenas.

This particular workshop was attended by various representatives of industry and was coordinated by Dr. Vladimir Semak of ARL Penn State. Dr. Semak conducted two presentations: "An Introduction to Laser Process Simulations" and "Applications of Physical Models in Laser Processing Practice". These presentations were followed by Oak Ridge National Laboratory's Dr. Suresh Babu's talk on "Simulation of Material's Response to Laser Processing." Dr. Vital Prabhu of Penn State's Industrial Engineering Department also provided a discussion on "Optimal Organization of Manufacturing Systems."



Members of the U.S. Air Force Research Laboratory stop by to visit ARL's Navy ManTech booth.

NASTC

The first annual National Aerospace Science and Technology Conference hosted by the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base was held recently at the Dayton Convention Center in Ohio. iMAST participated in the event with an exhibit booth featuring various on-going aeronautical engineering efforts within the scope of the Navy ManTech Program. The conference provided ARL an opportunity to interface with U.S. Air Force-related efforts in the areas of materials processing, high energy processing, repair, and transmission technologies.

CALENDAR OF EVENTS

26–30 Nov	Defense Manufacturing Conference 2000 ★★★★★ visit the iMAST booth	Tampa, FL
28–30 Jan 2001	NDIA Tactical Wheeled Vehicle Conference	Monterey, CA
3–5 Apr	AW&ST Maintenance, Overhaul and Repair Conference	Dallas, TX
10–12 Apr	Navy League Sea-Air-Space Expo 2001	Washington, D.C.
9–11 May	American Helicopter Society Forum 57 ★★★★★ visit the iMAST booth	Washington, D.C.
22–23 May	Materials and Manufacturing Advisory Board Meeting	State College, PA
Fall TBA	Second Annual ONR Naval-Industry R&D Conference ★★★★★ visit the iMAST booth	Washington, D.C.
10–13 Sep	NDIA Joint Undersea Warfare Technology Conference	Groton, CT
18–20 Sep	Marine Corps League Expo ★★★★★ visit the iMAST booth	Quantico, VA
24–26 Sep	NDIA Combat Vehicles Conference	Ft. Knox, KY
29 Oct–2 Nov	NDIA Expeditionary Warfare Conference	Panama City, FL
26–29 Nov	Defense Manufacturing Conference 2001 ★★★★★ visit the iMAST booth	Las Vegas, NV

Quotable

“We’re going to press the comfort zone of technologists, because they’re going to have to think a lot harder and differently, and industry is going to be pressed in that they really have to come up with some new concepts.”

—Michael Andrews, Chief Scientist, Office of the Assistant Secretary of the Army for Research and Technology

PENNSTATE



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